

## **Impact of Typhoons on the Western Pacific Ocean DRI: Numerical Modeling of Ocean Mixed Layer Turbulence and Entrainment at High Winds**

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### **LONG-TERM GOALS**

This study contributes to our long-term efforts toward understanding:

- Mixed layer dynamics
- Processes that communicate atmospheric forcing to the ocean interior

### **OBJECTIVES**

This ongoing collaborative effort is measuring and modeling the response of the upper ocean to strong typhoons both in simple, open ocean conditions and in the more complex conditions caused by ocean eddies and preconditioning by prior storms. The measurement and modeling activities include a focus on the impact of surface waves, air-sea fluxes and the temperature, salinity and velocity structure of the upper ocean. The goals of this effort are to understand key upper ocean processes, test upper ocean models, develop and test new parameterizations of upper ocean physics used and study the feedback from the ocean to typhoon intensity.

### **APPROACH**

The approach of the the modeling component is to use field observations to force Large Eddy Simulation (LES) and upper ocean turbulence models in equivalent numerical cases and to use model-data comparison to test the theoretical basis of mixed layer turbulence scalings and parameterizations. The strategy is to test our physical theories and parameterizations of mixed layer dynamics against data by incorporating them realistically in turbulence-resolving LES models with embedded virtual measurements. Verification of the underlying theories can then be achieved through direct model-data comparison, using observations of ocean waves and turbulence under a wide range of oceanic conditions, and leading to improved parameterizations of upper ocean turbulence. The strong and isolated wind forcing in tropical cyclones provides an ideal environment for testing theories and parameterizations of the role of surface waves in the ocean mixed layer. This follows similar work in CBLAST exploiting the comprehensive view of boundary layer turbulence made possible by the combination of Lagrangian float and EM-APEX measurements. In FY2011, work has continued on developing an improved second moment closure to represent the impact of Langmuir turbulence. This

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model is remarkably novel because it involves a vertical momentum flux that is directed down the gradient of surface wave Stokes drift, in addition to the conventional one proportional to the Eulerian (non-wave) shear.

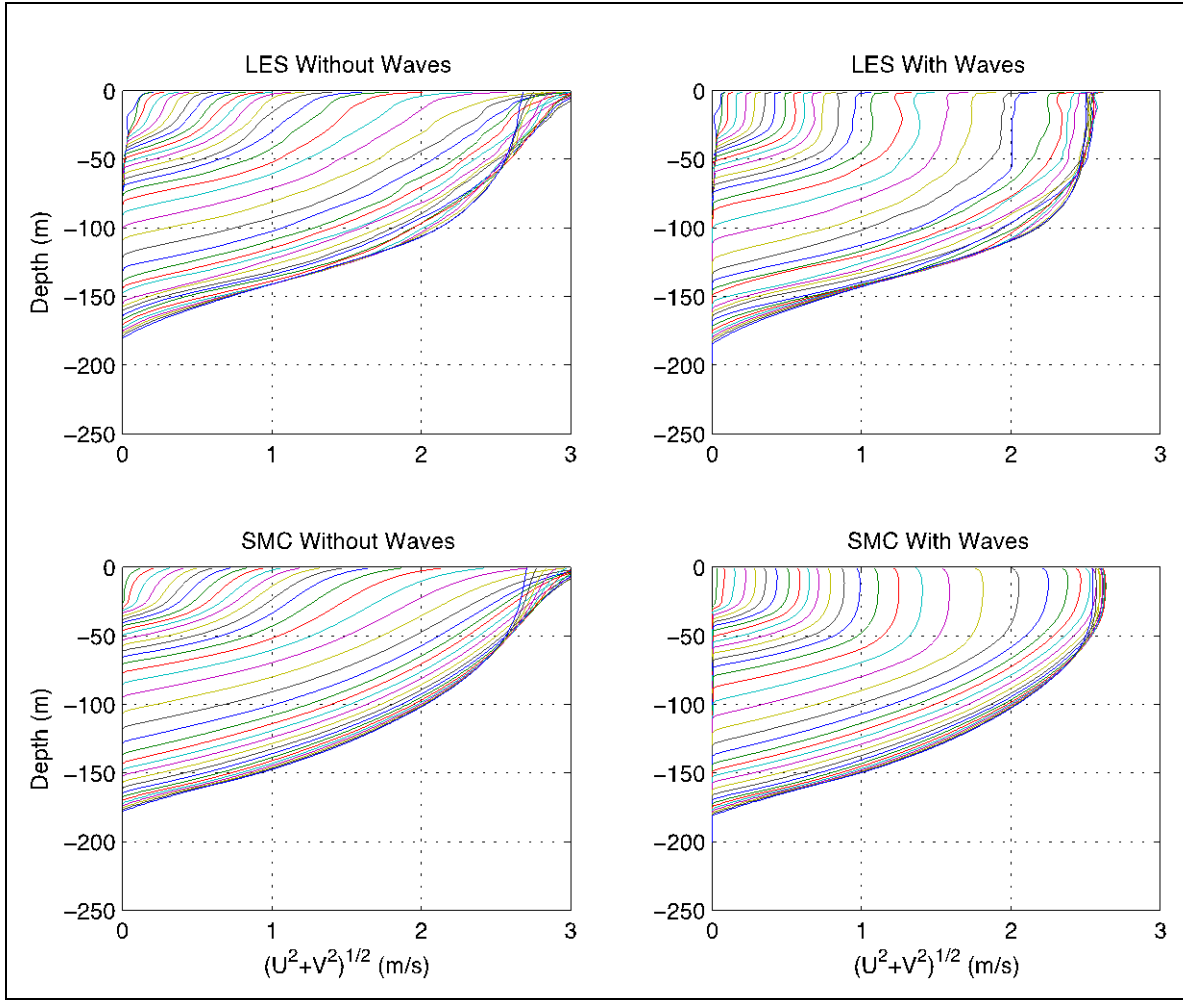
## WORK COMPLETED

Following generally positive comparisons between LES models and Lagrangian float observations in Harcourt & D'Asaro (2008), and subsequent refinements in the interpretation of observations in Harcourt & D'Asaro (2010), a closure model based primarily on the Craik-Leibovitch (CL) vortex force has been developed to predict upper ocean turbulence, including under the winds of tropical cyclones. This model more correctly represents the effect of these vortex force terms due to the interaction of surface wave Stokes drift and Eulerian current shear within the mixed layer. This manuscript (Harcourt, *submitted to JPO*) is under minor revision and acceptance is anticipated shortly. Further development of the model has transferred the treatment of Craik Leibovitch vortex force terms into the GOTM modeling framework (Burchard and Bolding, 2000) that encompasses several other versions of second moment closures.

## RESULTS

The new model is remarkable in that it *derives* significant modifications to the popular  $q^2l - q^2$  Mellor-Yamada 2.5 parameterizations due to the Craik-Leibovich vortex force. The modifications come primarily in two components: the first is that additional forcing terms are included in the equilibrium model, or algebraic closure, that underpins 'stability functions' which relate turbulence velocity and length scales to eddy viscosities and diffusivities. The second is through a component of the momentum flux that is forced by its derivation to be directed down the gradient of Stokes shear. This second component of momentum flux has been foreshadowed by empirical considerations in efforts to understand prior results from LES studies of Langmuir turbulence (Smyth et al., 2002; Sullivan & McWilliams 2004; 2007; and McWilliams et al. 2012).

The new second moment closure model places the down-Stokes-gradient momentum flux on firm theoretical grounds and accounts for the much more well-mixed Eulerian momentum profiles in high resolution simulations with wave effects. Less striking but more important in the long term are the significantly modified stability functions, as they it pave the way for accurate and comprehensive approaches to the interplay between wave- and non-wave-related upper ocean forcing in both Mellor-Yamada and other mixed layer parameterizations. These modifications go well beyond the additional production of turbulent kinetic energy (TKE) in Kantha & Clayson (2004) or D'Alessio et al (1998) because they account for the very different mixing impacts of production into the different components of TKE. It therefore provides a more inclusive approach than basing upper ocean models on VKE scaling predictions of wave impacts, such as those in Harcourt and D'Asaro (2008) or Belcher et al. (*submitted to GRL*).



**Fig. RRH1. Simulations of upper ocean shear below the passage of a tropical cyclone, compared between the new second moment closure (SMC) and turbulence-resolving LES, both with and without including the Craik-Leibovitch effect due to the Stokes drift of surface waves.**

The new turbulence models improves model-data comparisons of upper ocean shear (Fig 1) below typhoons and hurricanes, but it is not without significant defects in comparisons with Lagrangian float-observed vertical kinetic energy (i.e. D’Asaro, 2001). In the past quarter since submitting the first version of this model, significant efforts have been put into recasting its salient impacts into the framework general ocean turbulence model (GOTM; Burchard and Bolding, 2000). Adapting the changes driven by properly including the CL vortex force in the Reynolds Stress closure into the GOTM framework was motivated by both larger class of expressions implemented for pressure-strain closure and by the different approach to modeling the turbulence length scale under the generic length-scale equation of Umlauf and Burchard (2003).

Following this plan, a generalized closure including the correct CL vortex production terms was composed as a relatively large linear algebra problem and solved using a symbolic math program. While the resulting expression is a complex function of closure constants, the solution gives the stability functions (for determining eddy coefficients) as ratios of polynomials in the local

nondimensional forcing scales of stability, Eulerian shear, Stokes shear, and the product of Stokes and Eulerian shear, and the expressions are straightforward to compute. This was a significant achievement, but analyzing the new algebraic solution (relating vertical eddy coefficients to energy and dissipation or its length scale) showed the improved model based on the GOTM framework to be not significantly better than the earlier one (Harcourt, *submitted to JPO*). While the GOTM framework contains many more closure expressions for the problematic pressure-strain correlations of Langmuir turbulence, none of these have quite the form needed to improve the model even as the coefficients are fit to LES solutions of upper ocean turbulence ranging between moderate to very high winds and with variable sea states.

Attempts to compare model behavior with the most remarkable wave-related features of typhoons and hurricanes has been mixed. While there is generally an agreement between vertical kinetic energy measured by floats and the second moment closure predictions in their mixed layer averages, their profiles differ significantly due to the inadequate closure of the pressure-strain correlation terms mentioned above. More troubling, Lagrangian float measurements immediately behind the eye of tropical cyclones show a drop in vertical kinetic energy not yet directly reproduced by the closure or by the LES in simulations based on measured winds and the Stokes drift from modeled wave spectra. There is considerable uncertainty in surface forcing and it may well be that the modeled wave spectra and winds in this rear quadrant are not accurate as there is a well-grounded expectation that vertical mixing driven by the CL vortex force will be significantly inhibited when the wind and waves are perpendicular, but in the mean time presenting a clear verification of this phenomenon using direct model-data comparisons has not yet been achieved.

## **IMPACT/APPLICATIONS**

Surface waves are believed to play a key role in the upper ocean boundary layer, yet do not appear explicitly in any of the major boundary layer parameterizations used in ocean circulation or climate models. Addressing this defect will lead to mixed layer models with turbulence intensity and entrainment efficiency, scaled by wind stress, that increase with surface wave age, in the presence of swell. While subsurface shear may dominate pycnocline mixing under inertially resonant wind forcing conditions, variability in mixed layer energy due to surface waves will play a significant role in deepening the layer when this is not the case. A boundary layer model that includes sea state dependencies, in addition to the usual dependencies on surface stress, buoyancy flux, and subsurface shear, will ultimately be more accurate than one which does not.

## **RELATED PROJECTS**

Typhoons DRI continues previous work in the Hurricane component of CBLAST DRI. Development of the field program system for archiving and serving images and compact data to ship science parties has been done in conjunction with work in the LatMix DRI.

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## **PUBLICATIONS**

- Harcourt, R. R., 2012: A second moment closure model of Langmuir turbulence. *submitted to J. Phys. Oceanogr.* [refereed, currently under minor review].